PHYSICAL REVIEW C VOLUME 21, NUMBER 4 APRIL 1980

Gamma-gamma directional correlations for transitions in ^{84}Kr

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(Received 1 June 1979)

The directional correlation of coincident γ transitions in ^{84}Kr have been measured following the decay of 32 min ^{84}Br using a Ge(Li)-NaI(Tl) spectrometer. Measurements have been carried out for ten gamma cascades, resulting in the following multipole mixing ratios: $\delta(605) = +0.01 \pm 0.01$, $\delta(736) = -0.07 \pm 0.01$, $\delta(802) = -0.04 \pm 0.01$, $\delta(987) = -0.08 \pm 0.01$, $\delta(1016) = +0.80 \pm 0.03$, $\delta(1741) = -1.05 \pm 0.07$, $\delta(1877) = -0.07 \pm 0.03$, and $\delta(2484) = +0.01 \pm 0.01$. These data permitted assignments of spins to the levels at 2345 (4^+), 2623 (2^+), 2759 ($2^\pm$), 3082 ($3^\pm$), 3366 keV ($1^\pm$) and confirmed previous assignments for the 1898 (2^+), 2095 (4^+), and 2700 keV (3^-) levels. A comparison of some properties of the 2_2^+ and 2_1^+ states in ^{84,82,80}Kr and in other even-even nuclei (Ru, Pd, and Cd) is also presented.

[RADIOACTIVITY ^{84}Br from fission of U; measured $\gamma\gamma(\theta)$. ^{84}Kr levels deduced J, π, δ.]

I. INTRODUCTION

The low lying states of even-even nuclei in the mass range $60 \leq A \leq 150$ are usually described as the vibrations about a spherical equilibrium shape, as rotations of a soft deformed core or as the excitations of two quasiparticles from the ground state. These various models lead to quite different predictions for the electromagnetic transition probabilities. A systematic investigation of quantities such as the multipole mixing ratios $\delta(E2/M1)$ for γ transitions is therefore of considerable importance in providing a better understanding of the structure of these nuclei in terms of collective or single particle effects. Recently the data on $E2/M1$ mixing ratios were tabulated by Krane.[1] In particular the de-excitation of 2_2^+ levels of even-even spherical nuclei has been considered in many publications.[2-4] Attention is drawn to the fact that these mixing ratios vary systematically with the neutron number in many nuclei, and in addition it has been shown[2] that the systematic behavior of the $E2/M1$ mixing ratios for the $2_2^+ \rightarrow 2_1^+$ transitions can be interpreted with reasonable success across the entire mass range by considering only a few low lying two-quasiparticle states as a perturbation of the phonon states. The importance of the $\delta(E2/M1)$ as real nuclear observables has been emphasized, and it is expected that these can be related in a model dependent way to the details of the nuclear structure.

The excited states of ^{84}Kr have been studied previously from the decay of ^{84}Br (Refs. 5–7) as well as ^{84}Rb (Refs. 8 and 9). The spins and parities were assigned from the γ-ray intensities and logft values; however, these assignments are not unique except for a few very low lying states. A good deal of nuclear reaction work has been carried out on ^{84}Kr nucleus and these include the results of $(\alpha, 2n\gamma)$,[10] (p, t),[11] and (p, p')[12] reactions, neutron capture measurements,[13] and Coulomb excitation.[14] In spite of all this work comparatively little is known about the level structure of ^{84}Kr and several spin assignments remain ambiguous. The angular correlation of the 1016–882-keV cascade is the only previously reported measurement of this kind and was carried out using NaI(Tl) detectors and following the decay of ^{84}Rb.[8] The decay of ^{84}Rb, however, populated levels in ^{84}Kr up to only 1.9 MeV and in order to study the levels of higher energies it is essential to populate these following the decay of ^{84}Br. The present investigation was undertaken with a view to measure the directional correlations for several γ cascades in order to determine the spins of the excited states in ^{84}Kr and to obtain the values of multipole mixing ratios $\delta(E2/M1)$ for a number of γ transitions in this nucleus. The measurements on ^{84}Kr γ cascades were carried out from the ^{84}Br decay and using a Ge(Li)-NaI(Tl) spectrometer. A total of ten γ cascades have been measured in the present study involving an equal number of levels in ^{84}Kr.

II. EXPERIMENTAL

The radioactive source of ^{84}Br was prepared by chemically separating it from other fission products of uranium. Approximately 1 g of uranyl nitrate hexahydrate was irradiated with neutrons at a flux of 5×10^{12} n/cm^2 sec for 30 minutes in the

IEA-Rl reactor. The bromine activity was separated five minutes after the end of the irradiation using a method similar to the one described by Kelinberg and Cowan.[15] Finally the precipitate of AgBr was dissolved in two drops of 1M solution of sodium thiosulphate and transferred to a Lucite container. The source dimension was 5 mm × 2.5 mm and it was ready for counting approximately 30 minutes after the end of the irradiation.

The γ spectrometer consisted of the combination of a 40-cm^3 true coaxial Ge(Li) detector and a 7.6 × 7.6-cm NaI(Tl) detector. The γ-γ coincidences were recorded using a standard low noise fast coincidence system ($2\tau = 70$ nsec) and a 4096-channel pulse height analyzer. The measurements were carried out at angles from 90° to 270° in steps of 30°. The movable NaI(Tl) detector changed angles automatically every five minutes routing the coincidence spectrum from the Ge(Li) detector to the appropriate subgroup of the analyzer memory. The counting with a single source was for a period of 80 minutes and a total of 80 sources were used for the entire experiment.

The SCA (single channel analyzer) windows were set to accept the photopeaks at 882 and 1898 keV in the NaI(Tl) detector spectrum. Figure 1(d) shows the spectrum from the NaI(Tl) detector with the positions of the gates indicated. The intensities of the coincident γ rays were measured from the Ge(Li) detector spectra recorded at various angles and corrected for the chance coincidences and the source decay. The chance coincidences were determined separately

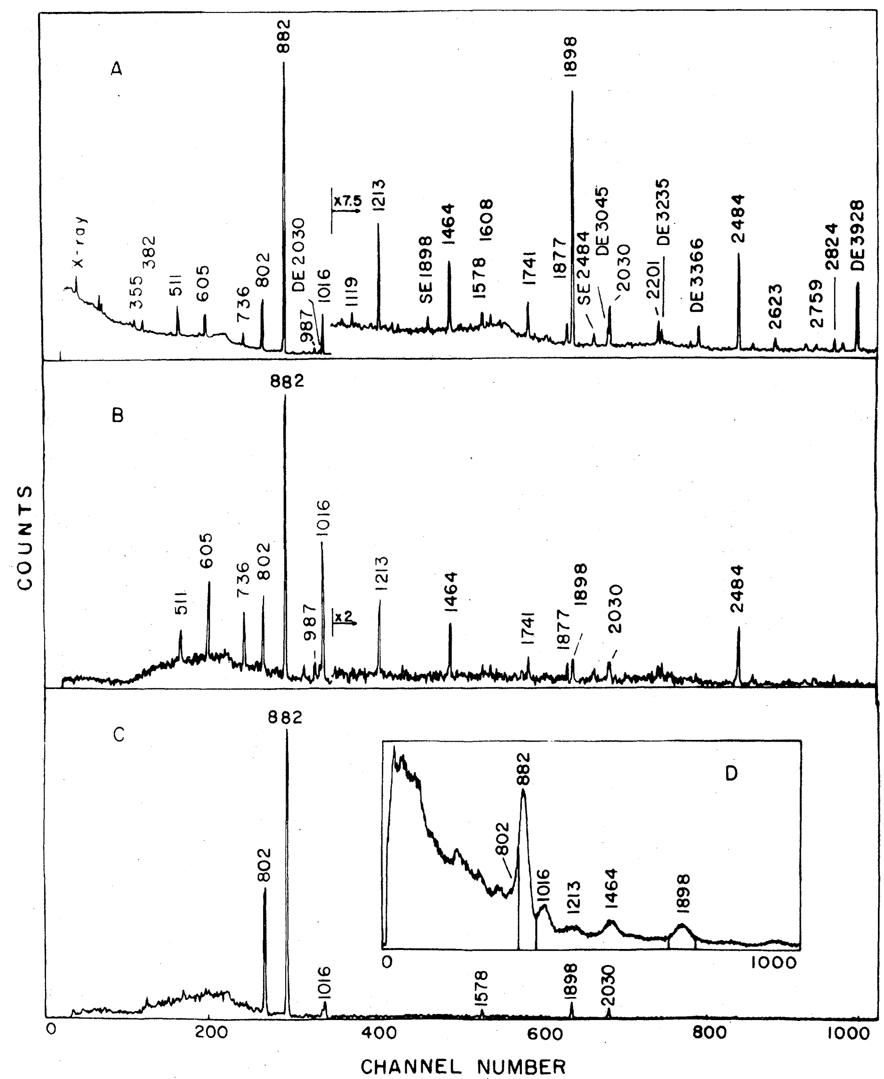

FIG. 1. Direct γ-ray spectrum up to 3 MeV in the decay of ^{84}Br observed with the Ge(Li) detector (A) and the γ-ray spectra coincident with the photopeaks at 882 keV (B) and 1898 keV (C). In the inset is shown the direct γ-ray spectrum observed with the NaI(Tl) detector (D).

for each gate setting by introducing a delay of 1 μsec in the pulses from one of the detectors before reaching the coincidence unit and recording the coincidence spectrum. The effects of Compton scattered radiation of high energy γ rays included in the window setting were negligible in most cases and were not taken into consideration. The angular correlation coefficients A_{kk} were determined by a least square fitting procedure in the usual manner. The convention of Becker and Steffen[16] has been used to define the multipole admixture δ.

III. RESULTS

The low energy γ-ray spectrum in the decay of ^{84}Br obtained with the Ge(Li) detector is shown in Fig. 1. The spectrum shows all the γ rays observed by Hill and Wang[7] and Hattula *et al.*[6] in this energy region. The contributions from the six minute ^{84m}Br decay were neglibible as this activity decayed sufficiently during the course of chemical separation. Typical γ spectra observed in coincidence with the 882 and 1898 keV photopeaks are also shown in Fig. 1.

The directional correlation coefficients A_{kk} obtained from the present measurements for various γ cascades are given in Table I. The experimental values of A_{kk} have been corrected for the finite solid angle effects of the detectors.[17,18] The multipole mixing ratios for the γ transitions together with the spin sequence most consistent with the observed correlation data and the decay properties are also presented in Table I.

Some typical results of the direction correlation measurements are shown in Fig. 2. The point at 90° has been normalized to unity in each case. Each experimental point is shown with the error bar, and the solid curve is the least square fit of the experimental data to the function

$$W(\theta)=1+A_{22}P_2(\cos\theta)+A_{44}P_4(\cos\theta).$$

The parametric plots for some of the relevant spin sequences are shown in Fig. 3. The corrected values of A_{kk} with the associated errors have been displayed as (A_{22}, A_{44}) points in this plot. A partial energy level scheme of ^{84}Kr taken from the results of Hill and Wang[7] is shown in Fig. 4. Only γ transitions of interest in this study are shown. The spin and parity assignments deduced from the present investigation and supported by other available data are included in this figure.

The assignment of the ground state of ^{84}Kr is 0^+ as for all even-even nuclei, and the 2^+ assignment for the 882 keV state follows from the Coulomb excitation study.[14]

The spin and parity of the 1898-keV state is believed to be 2^+ based upon the previous angular correlation measurement of the 1016-882-keV γ cascade following the ^{84}Rb decay.[8] The present measurements confirm the 2-2-0 spin sequence for this cascade; however, the A_{kk} values differ considerably from the results of Ref. 8. We believe that the systematic errors introduced by the prolonged duration of measurement combined with the poor counting statistics in the previous measurements may be the cause of this discrepancy. The total number of true coincidences obtained for this cascade in the present measurement was approximately 7000 per angle as compared to 600 coincidences per angle by the authors of Ref. 8 (only three angles were used by these authors). The present A_{kk} values give, for the multipole mixing ratio of the 1016-keV transition, $\delta=+0.80\pm0.03$ or $+2.96\pm0.74$ [theoretical expressions of A_{kk} are quadratic functions of the mixing ratio (see, e.g.,

TABLE I. Results of directional correlation measurements on γ transitions in ^{84}Kr.

Energy level (keV)	Gamma cascade	A_{22}	A_{44}	Spin sequence	Mixed transition	Multipole mixing ratio $\delta(E2/M1)$
1898	(a) 1016–882	-0.235 ± 0.014	0.164 ± 0.022	2(1,2)2(2)0	1016	$+0.80\pm0.03$
		-0.056 ± 0.050 [a]	0.426 ± 0.089			>10
2095	(b) 1213–882	0.108 ± 0.023	0.008 ± 0.036	4(2)2(2)0		
2345	(c) 1464–882	0.078 ± 0.026	0.030 ± 0.070	4(2)2(2)0		
2623	(d) 1741–882	0.429 ± 0.044	0.163 ± 0.070	2(1,2)2(2)0	1741	-1.05 ± 0.07
2700	(e) 802–1898	-0.106 ± 0.027	0.046 ± 0.047	3(1,2)2(2)0	802	-0.04 ± 0.01 [b]
2700	(f) 605–1213–882	-0.161 ± 0.019	0.023 ± 0.030	3(1,2)4(2)2(2)0	605	$+0.01\pm0.01$ [b]
2759	(g) 1877–882	0.317 ± 0.049	0.013 ± 0.079	2(1,2)2(2)0	1877	-0.07 ± 0.03
3082	(h) 736–1464–882	-0.067 ± 0.024	-0.050 ± 0.038	3(1,2)4(2)2(2)0	736	-0.07 ± 0.01
3082	(i) 987–1213–882	-0.067 ± 0.036	-0.021 ± 0.056	3(1,2)4(2)2(2)0	987	-0.08 ± 0.01
3366	(j) 2484–882	-0.252 ± 0.028	0.053 ± 0.041	1(1,2)2(2)0	2484	$+0.01\pm0.01$

[a] Value from Ref. 8.
[b] Values are for $\delta(M2/E1)$.

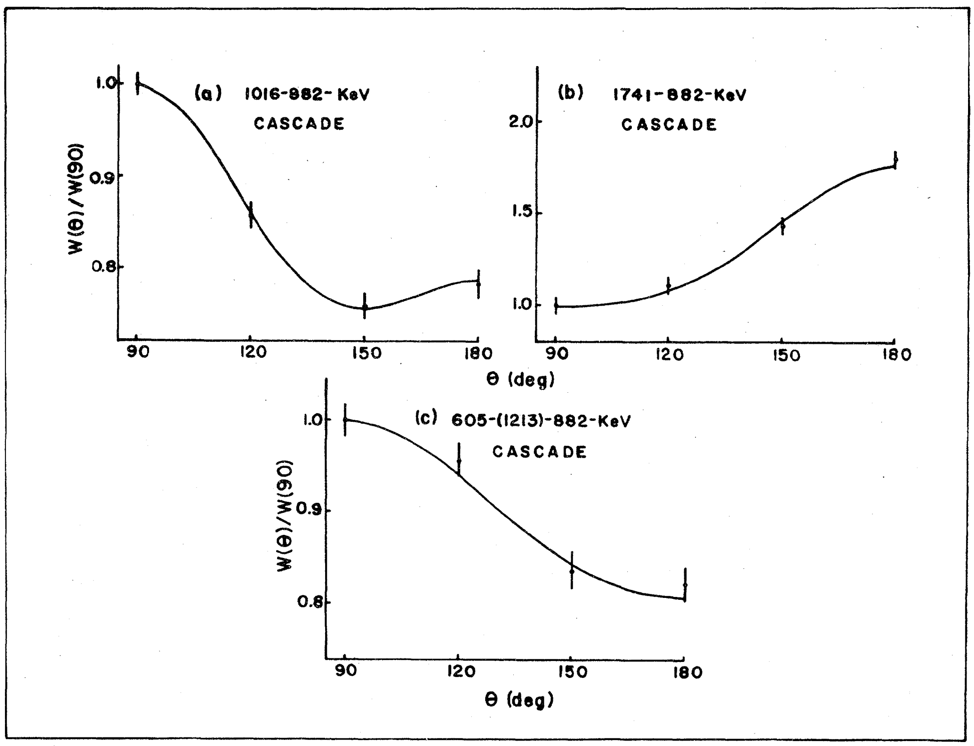

FIG. 2. Directional correlation curves for some gamma cascades typical of (a) intense transitions, (b) weak transitions, and (c) transitions involving a skipped intermediate transition. Solid curves are the least square fits to the polynomial $W(\theta)=1+A_{22}P_2(\cos\theta)+A_{44}P_4(\cos\theta)$.

Ref. 16) and in general give two solutions for the δ]. The χ^2 analysis, however, favors the lower value. The choice of the lower value in this case may also be reasonable considering the observed systematic variations in the $2_2^+ \to 2_1^+$ transition mixing ratios in several groups of nuclei, e.g., see Table II.

The results for the 1213–882-keV γ cascade measured from the 882-keV gate show good agreement with the A_{kk} coefficients expected for a 4-2-0 spin

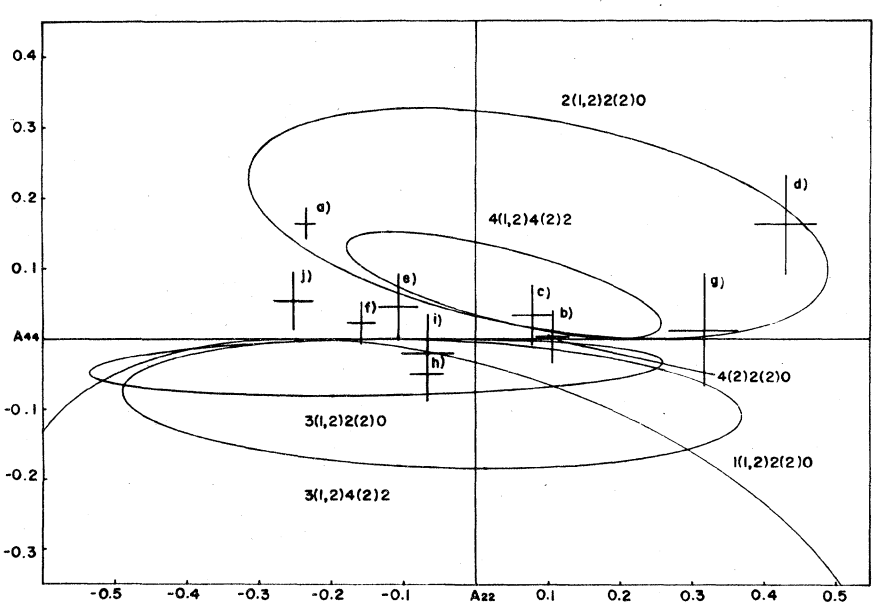

FIG. 3. Parametric plots for various spin sequences showing the experimental A_{22} and A_{44} points with error bars.

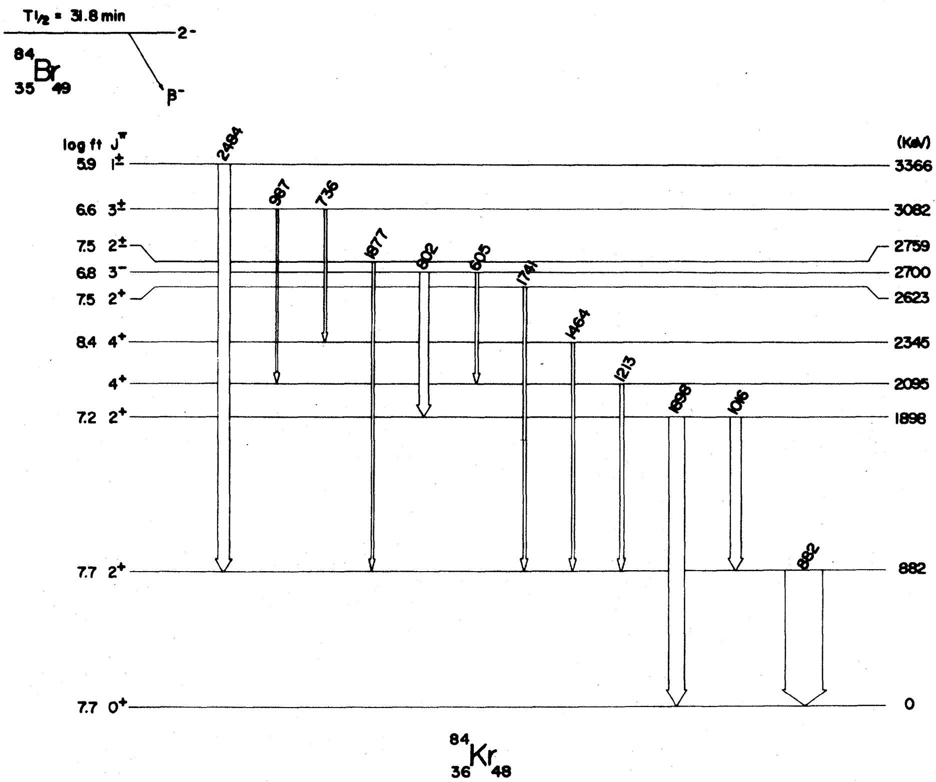

FIG. 4. Partial decay scheme of ^{84}Br to the levels in ^{84}Kr.

sequence, thereby confirming the 4^+ assignment for the 2095-keV state already proposed from the decay studies[7] and the reaction work.[12]

The log*ft* value of 8.4 for the beta feeding[7] allows the possibility of spins between 0 and 4 for the 2345-keV level. The results of the (p,p') reaction,[12] however, assigned a 4^+ to this level identifying this state with the one found at 2337 keV in

TABLE II. Some of the properties of 2_1^+ and 2_2^+ states in Kr isotopes compared with the Ru, Pd, and Cd isotopes.

	$E_{2_1^+}$ (keV)	$E_{2_2^+}$ (keV)	$B(E2,\ 2_1^+ \to 0^+)$ $10^{-2}(eb)^2$	$\frac{B(E2,\ 2_2^+ \to 0^+)}{B(E2,\ 2_1^+ \to 0^+)}$	$2_2^+ \to 2_1^+\ \delta(E2/M1)$
$^{80}_{36}Kr_{44}$	618	1260	6.8	0.016	$+17^{+80}_{-9}$
$^{82}_{36}Kr_{46}$	777	1476	3.5	0.018	$+2.6 \pm 0.2$
$^{84}_{36}Kr_{48}$	882	1898	3.0	0.073	$+0.80 \pm 0.03$
$^{102}_{44}Ru_{58}$	475	1102	15	0.038	-60 ± 20
$^{104}_{46}Pd_{58}$	556	1345	11	0.060	$+30^{+\infty}_{-22}$
$^{106}_{48}Cd_{58}$	633	1715	9.3	0.31	-0.90 ± 0.2
$^{104}_{44}Ru_{60}$	358	895	19	0.049	-9 ± 2
$^{106}_{46}Pd_{60}$	512	1120	13	0.024	-7 ± 2
$^{108}_{48}Cd_{60}$	633	1601	11	0.097	$-1.5^{+1.5}_{-0.6}$
$^{108}_{46}Pd_{62}$	434	928	15	0.013	-3.1 ± 0.4
$^{110}_{48}Cd_{62}$	658	1467	10	0.041	-1.2 ± 0.2
$^{110}_{46}Pd_{64}$	374	815	19	0.014	-5^{+2}_{-1}
$^{112}_{48}Cd_{64}$	617	1308	11	0.036	-0.77 ± 0.06

that work. The A_{22} value for the 1464–882-keV γ cascade, although somewhat lower than the expected $A_{22}=0.102$ for the 4-2-0 spin sequence, agrees within the experimental error. The slight discrepancy may be explained by considering that there may be some contribution from the 2484–882-keV cascade (with negative A_{22}) included in the above result. The double escape of the 2484-keV photopeak is at 1462 keV and could not be resolved from the 1464-keV photopeak. The present result therefore supports the 4^+ assignment of the 2345-keV level.

The A_{kk} values for the 1741–882-keV γ cascade clearly indicate the 2-2-0 spin sequence and therefore establish the spin of the 2623-keV level as 2. The mixing ratio of the 1741-keV transition is calculated from the experimental values of A_{kk} to be -1.0 ± 0.07. This result implies a positive parity for the 2623-keV level. Negative parity will result in an unreasonably large $M2$ admixture in the 1741-keV transition.

The angular correlation result of the 605–(1213)–882-keV cascade is consistent with spin sequences 5-4-2-0 as well as 3-4-2-0. However, a spin of 5 for the 2700-keV level is unlikely because the log*ft* value of 6.8 for the beta decay to this level and strong γ transitions from the level to the 4^+ and 2^+ states at 2095 keV and 1898 keV, respectively, limit the spin of this state to 2 or 3. Result of the angular correlation of the 802–1898-keV cascade is consistent both with the 2-2-0 and 3-2-0 spin sequences. The combined results of these two cascades along with the beta and gamma decay studies therefore suggest a spin of 3 for the 2700-keV level. The results of (p,t)[11] and (p,p')[12] reaction studies assign a 3^- for this level. The present results are consistent with this assignment as both 605- and 802-keV transitions are predominantly dipole in character.

The A_{kk} values for the 1877–882-keV γ cascade indicate a 2-2-0 spin sequence establishing a spin of 2 for the 2759-keV level. This result is consistent with the beta decay study[7] which indicates the spin of this level as 1 or 2.

The log*ft* value[7] limits the spin of the 3082-keV level to 1, 2, or 3; however, relatively strong γ transitions at 736 and 987 keV feeding 4^+ levels at 2345 and 2095 keV, respectively, rule out the spin 1. The combined results of the angular correlations of 736–1464–882 and 987–1213–882-keV γ cascades indicate the spin 3 for this level. This level was assigned as 3^- on the basis of angular distributions from the (p,t)[11] reaction.

The beta and gamma decay studies[7] suggest a spin of 1 or 2 for the 3366-keV level. The angular correlation results for the 2484–882-keV γ cascade are consistent with these assignments but show a better fit with the 1-2-0 spin sequence.

IV. DISCUSSION

The present investigation has yielded the $E2/M1$ mixing ratios for a number of γ transitions in ^{84}Kr and has removed several ambiguities regarding the spin assignments to the excited states up to 3.4 MeV. The multipole mixing ratio of the 1016-keV $2_2^+\to2_1^+$ transition is determined to be $+0.80\pm0.03$. The corresponding $2_2^+\to2_1^+$ transitions in ^{80}Kr ($\delta=17^{+80}_{-9}$) (Ref. 19) and ^{82}Kr ($\delta=+2.6\pm0.2$) (Ref. 20) show considerably larger quadrupole content. In Table II are presented some of the results taken from the compilation of Krane[2] (and references therein) for the isotopes ^{80}Kr, ^{82}Kr, and ^{84}Kr and compared with several groups of isotones of Ru, Pd, and Cd nuclei to illustrate the similarities observed in some of their properties. The Ru, Pd, and Cd nuclei contain 44, 46, and 48 protons, respectively, which are equal to the numbers of neutrons in ^{80}Kr, ^{82}Kr, and ^{84}Kr, respectively. In each group of nuclei it is noted that the energies of the 2_1^+ and 2_2^+ states increase with the increasing number of neutrons/protons in going from 44 to 48 while the magnitude of $\delta(E2/M1)$ for the $2_2^+\to2_1^+$ transition decrease (the sign of δ stays constant within the group, ^{104}Pd being an exception). As the energies of these states increase, the quasiparticle contributions to the states also presumably increase with the result that they are expected to be less collective. This fact is also borne out by the decreasing $B(E2,\ 2_1^+\to0^+)$ values and increasing $B(E2,\ 2_2^+\to0^+)/B(E2,\ 2_1^+\to0^+)$ ratios in going from 44 to 48 nucleons.

While considering only the placement of the energy levels, their spins and parities, it appears that ^{84}Kr has the expected level structure of a vibrational even-even nucleus. For example, the one-phonon 2^+ state at 882 keV and the two-phonon triplet ($0^+, 2^+, 4^+$) at 1837, 1898, and 2095 keV, respectively, are clearly identifiable. The ratio of the average energy of the two-phonon triplet to the one-phonon state is approximately 2.2 as compared to 2.0 expected from the simple vibrational model. The 3^- state at 2700 keV proposed in the previous studies and confirmed by the present angular correlation results most probably corresponds the one-octupole-phonon vibration. However, there is no clear identification of the three-quadrupole-phonon levels ($0^+, 2^+, 3^+, 4^+$, and 6^+) expected near 2700-3100 keV. The 4^+ state at 2345 keV is too low in energy to be considered the member of the three-phonon quintet; besides, it preferentially populates the one-phonon state contrary to the expectation of the model. Similarly, the states at 2623 and 2759 keV also preferentially populate the one-phonon state and probably do not correspond to the three-phonon multiplet.

The main difficulty arises when one considers the electromagnetic properties of the γ transitions between the levels in ^{84}Kr. The present results show that several transitions have quite large $M1$ admixture, and these are difficult to explain in terms of simple vibrational model. In particular, the $2_2^+ \rightarrow 2_1^+$ transition is forbidden as $M1$ if the states are considered pure phonon states. Hence it appears that an interpretation of the excited states of ^{84}Kr in terms of simple vibration model is of limited value. Recently, Krane[2] in a modified approach introduced a small admixture of two-par-particle state into the phonon state vector (treating it as perturbation) in order to explain the presence of $M1$ transitions. He had reasonable success in predicting the values of the multipole mixing ratios $\delta(E2/M1)$ for the $2_2^+ \rightarrow 2_1^+$ transitions in a large number of nuclei in the mass range $58 \leq A \leq 150$. The signs of the δ are not predicted uniquely; however, more refined calculations using the relevant parameters for the nucleus under consideration are necessary for such detailed comparison. We hope that the present results will be useful for some such future calculations.

ACKNOWLEDGMENTS

The authors would like to thank the staff of IEA-Rl reactor for their efficient help in the irradiation of samples. One of us (F.C.Z.) acknowledges the hospitality at the IEA. Partial financial support for this work was provided by the Comissao Nacional de Energia Nuclear (CNEN).

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